DIFFUSE GAMMA-RAYS FROM LOCAL GROUP GALAXIES

Vasiliki Pavlidou

and

Brian D. Fields

Department of Astronomy and Center for Theoretical Astrophysics
University of Illinois
Urbana, IL 61801, USA

ABSTRACT

Diffuse γ-ray radiation in galaxies is produced by cosmic ray interactions with the interstellar medium. With the completion of EGRET observations, the only extragalactic object from which there has been a positive detection of diffuse γ-ray emission is the Large Magellanic Cloud. We systematically estimate the expected diffuse γ-ray flux from Local Group galaxies, and determine their detectability by new generation γ-ray observatories such as GLAST. For each galaxy, the expected γ-ray flux depends only on its total gas content and its cosmic ray flux. We present a method for calculating cosmic ray flux in these galaxies in terms of the observed rate of supernova explosions, where cosmic ray acceleration is believed to take place. The difficulty in deriving accurate supernova rates from observational data is a dominant uncertainty in our calculations. We estimate the γ-ray flux for Local Group galaxies and find that our predictions are consistent with the observations for the LMC and with the observational upper limits for the Small Magellanic Cloud and M31. Both the Andromeda galaxy, with a flux of $\sim 1.0 \times 10^{-8}$ photons sec^{-1} cm^{-2} above 100 MeV, and the SMC, with a flux of $\sim 1.7 \times 10^{-8}$ photons sec^{-1} cm^{-2} above 100 MeV, are expected to be observable by GLAST. M33 is at the limit of detectability with a flux of $\sim 0.11 \times 10^{-8}$ sec^{-1} cm^{-2}. Other Local Group galaxies are at least two orders of magnitude below GLAST sensitivity.

Subject headings: gamma rays: theory — cosmic rays – Local Group

1. Introduction

All-sky EGRET images (Hunter *et al.* 1997) dramatically show that the γ-ray flux above 100 MeV is dominated by emission from the Galactic disk. This emission can be well understood (Strong 1996, Sreekumar *et al.* 1998, Hunter *et al.* 1997) in terms of cosmic ray interactions with the interstellar medium. At energies $\gtrsim 100$ MeV, the generation of diffuse $\gamma-$ray emission is dominated

by the decay of π^0 produced in collisions between cosmic ray nuclei and interstellar medium nuclei. At lower energies, the dominant emission mechanism is bremsstrahlung from energetic cosmic ray electrons. Given the prominence of the Milky Way diffuse γ-ray emission, it is natural to ask whether we can see the corresponding emission originating from other galaxies.

To explore the possibility of such a detection requires an understanding of the γ-ray emissivity due to interactions of cosmic rays with matter. The problem of calculating the γ-ray emissivity per hydrogen atom given a cosmic-ray spectrum has been treated in detail by Stecker (1970; 1973; 1988) and Dermer (1986), who have made use of both experimental data and theoretical models on the relevant collisional cross sections. The results of these studies are also consistent with more recent calculations by Mori (1997) who used Monte Carlo event simulators and recent accelerator data. These studies reproduce the Milky Way (MW) γ-ray flux quite well as a function of energy and angle on the sky (at least in the 30–500 MeV range; at higher energies, the situation is less clear, and inverse Compton scattering of a hard electron component may be important; see Strong, Moskalenko, & Reimer (2000)).

By combining this information with an estimate of the gas content and the cosmic ray flux level and spectrum for a given galaxy, one can arrive at a prediction for its total γ-ray flux. Extended studies of this kind have been made for the Magellanic Clouds. Fichtel *et al.* (1991) calculated the flux expected from the Large Magellanic Cloud (LMC). Their estimate of the cosmic ray flux was based on the assumption that the expansive pressures of the gas, magnetic field and cosmic rays are in dynamic balance with the gravitational attraction of matter. Subsequent EGRET observations (Sreekumar *et al* 1992) resulted in the detection of the LMC with a γ-ray flux consistent with the prediction by Fichtel *et al.* (1991).

Sreekumar & Fichtel (1991) arrived at three different predictions for the Small Magellanic Cloud (SMC) diffuse γ-ray flux, each one based at a different assumption for the level of the SMC cosmic ray flux: a dynamic balance among thermal, magnetic, and cosmic ray pressures (as in the case of the LMC); a constant ratio of cosmic ray electrons and protons (where the electron flux was deduced from observational synchrotron data); and a "universal" cosmic ray flux (at the same level as in the solar neighborhood). EGRET observations have not led to a positive detection of the SMC in high-energy γ-rays, placing an upper limit to the γ-ray flux which excludes the predictions based on a dynamic balance or a "universal" cosmic ray flux (Sreekumar *et al.* 1993, Lin *et al.* 1996). In this way, the debate over the origin of cosmic rays (Galactic versus extragalactic) was settled observationally and the cosmic rays were shown to be originating from within the Galaxy.

Apart from the Magellanic Clouds, the only other Local Group galaxy for which there have been theoretical γ-ray flux predictions is M31.[1] Özel & Berkhuijsen (1987) and Özel & Fichtel

[1]Theoretical studies have also been made for starburst galaxies such as M82 (Akyüz *et al.* 1991) and NGC253 (Paglione *et al.* 1996) since these objects were good candidates for detection by EGRET due to their high supernova rate and presumably high cosmic ray flux. However, no positive detection of these objects has been achieved (Blom *et al.* 1999).

(1988), based on the observational data available at the time for the distance and gas content of M31, concluded that if the cosmic ray flux in the Andromeda galaxy is comparable to that in the Milky Way, then the galaxy should be detectable by EGRET. However, Blom, Paglione, & Carramiñana (1999) showed that EGRET has not detected M31, and have instead placed an upper limit for its γ-ray flux lower than the theoretically predicted value of Özel & Berkhuijsen (1987).

In this work we systematically study the γ-ray emission from Local Group galaxies and its detectability; with the completion of EGRET observations and the prospect of the construction of new, more sensitive γ-ray observatories, such an investigation is timely. We survey the latest available data for the gas contents of various Local Group galaxies, with attention to the uncertainties in the observational inputs, and their impact on the predicted emission. We also present a new method for computing the global mean cosmic ray flux and, thus the γ-ray flux, from the observed properties of the extragalactic sources. To do this we use the ratio of the supernova (SN) rate in each galaxy to the supernova rate of the Milky Way to calibrate the magnitude of the cosmic ray flux. This association is justified by the fact that cosmic ray acceleration is believed to take place in supernova remnants, an idea supported both by theoretical arguments (e.g., Ellison, Drury, & Meyer (1997)) as well as observational evidence (e.g., Koyama *et al.* 1995, Combi *et al.* 1998). Furthermore, we find this method leads to an estimate of the LMC γ-ray flux which is in excellent agreement with the level observed by EGRET.

Our predictions for the Local Group will be testable by the forthcoming *Gamma-ray Large Area Space Telescope* (GLAST), which is predicted to be launched in 2005. The proposed design of GLAST, described in De Angelis (2000) and in the GLAST webpage (`http://glast.gsfc.nasa.gov`), is that of a 1 m^2 effective area detector, sensitive to energies from 20 MeV to 300 GeV, with a field of view of 2.4 sr. This large field of view will allow any individual source to be observed for 20% of the duty cycle when GLAST is operating in the normal sky-scanning mode. The single-photon angular resolution will be 3° at 100 MeV and about 0°.2 at 10GeV. The nominal predicted lifetime of the GLAST mission is 5 years, with a goal of 10 years of operation. These specifications imply a sensitivity for GLAST of $\sim 2 \times 10^{-9}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (5-σ detection for a point source at high Galactic latitudes after a 2-year all sky survey), better by more than an order of magnitude than that of EGRET.

Recent work by Digel, Moskalenko, Ormes, Sreekumar, & Williamson (2000) has drawn attention to GLAST's potential for observing the three brightest Local Group sources. These authors presented simulated maps of the diffuse emission from the Magellanic clouds using models of Sreekumar, and discussed the observability of M31 on the basis of current observational upper limits. Our work gives theoretical support to this effort, as we make a robust prediction that M31 will be detected by GLAST. By considering the entire Local Group, we also find that M33 could be detectable by GLAST.

In Section 2 we present the theoretical background of our calculations. We discuss the $\gamma-$ray emissivity per H atom for a given cosmic ray spectrum, by now established both theoretically and

observationally. The "leaky box" model for cosmic ray propagation leads to the prediction that the CR flux should be proportional to a mean SN rate in the galaxy under consideration. Using this fact and an estimate of the gas content of each galaxy of the Local Group, we arrive at a prediction for its γ-ray flux. In Section 3 we present the data on the SN rates of the MW and the galaxies under study as well as their gas contents. In Section 4 we describe our results, compare our predictions for the Magellanic Clouds and M31 with the EGRET observations, and compare these and predictions for other Local Group galaxies with the anticipated sensitivity of GLAST. Discussion of our findings and conclusions follows in Section 5.

2. Gamma-Ray Production

Inelastic collisions of high-energy cosmic ray protons with the interstellar medium protons results most frequently to the production of neutral pions (π^0) which then decay, with a probability $\sim 99\%$, to two gamma ray photons:

$$
\begin{aligned}
p + p \rightarrow \quad & p + p + \pi^0 \\
& \qquad\qquad \hookrightarrow \quad \gamma + \gamma
\end{aligned}
$$

If $\phi_E^p(T_p)$ is the differential energy spectrum of the cosmic ray protons (protons/(cm^2-s-GeV-sr)) and $\langle \zeta\, \sigma_\pi(T_p) \rangle$ is the inclusive cross-section for the production of π^0 from p-p collisions, then the total π^0 production rate per target H atom (Γ_{π^0}) is given by:

$$\Gamma_{pp\rightarrow\pi^0} = 4\pi \int_0^\infty dT\, \langle \zeta\, \sigma_\pi(T) \rangle\, \phi_E^p(T) \tag{1}$$

In the case of the Milky Way, various authors (Stecker 1970, 1973, 1988; Cavallo & Gould 1971; Stephens & Badhwar 1981; Dermer 1986; Mori 1997) have calculated Γ_{π^0}. The results are consistent with each other within errors. Here we adopt

$$\Gamma_{pp\rightarrow\pi^0} \approx 7.0 \times 10^{-26}\ \pi^0\, (\text{s - H atom })^{-1}\, . \tag{2}$$

There is an additional contribution to π^0 production by interactions involving nuclei with $A > 1$ either in cosmic rays or in the interstellar medium (predominantly $p + \alpha$ and $\alpha + \alpha$). This contribution increases the estimated pion production rate by a multiplicative factor (Stecker 1970), which, when including α as well as nuclei heavier than helium both in the cosmic rays and in the interstellar medium, is ~ 1.5 (e.g., Mori (1997) and refs. therein). Taking into account this correction and the fact that each pion produces two γ-rays, the *total* γ-ray emissivity per hydrogen atom from π^0 *decay only* is

$$q_\gamma^{\pi^0} = 2.0 \times 10^{-25}\ \text{ photons}\, (\text{s - H atom})^{-1}\ , \tag{3}$$

in good agreement with the theoretical calculations cited above. Equation (3) includes γ-rays of all energies. Now if we confine our interest in the energy range > 100MeV, this emissivity decreases

by a factor of 0.76. In the same energy range, Fichtel and Kniffen (1984) have estimated the contribution in the γ-ray emissivity from cosmic ray electron bremsstrahlung to be 55% of the flux produced by neutral pion decay. [2] In this way, we can calculate a total Galactic γ-ray emissivity per hydrogen atom, for photon energies > 100 MeV , originating by all π^0-producing CR-ISM collisions as well as bremsstrahlung radiation from cosmic ray electrons:

$$q_\gamma(> 100\text{MeV}) = 2.4 \times 10^{-25} \text{ photons / (s - H atom)}. \tag{4}$$

which is consistent with observational data (e.g., Digel *et al.* 1995)

In order to extend this calculation to galaxies other than our own, we must relate the γ-ray production and hence cosmic ray flux, to observable properties of the galaxies. We therefore must account for both the acceleration and propagation of cosmic rays, and their dependence on the galactic environment. The assumption that supernova explosions are the engines of CR *acceleration* is encoded in simple and direct way. Specifically, we will impose a scaling of the CR source (injection) rate Q_p with $\mathcal{R}_{\rm G}$, the mean SN rate in a specific galaxy G:

$$Q_p^G \propto \mathcal{R}_{\rm G}.$$

To describe the *propagation* of cosmic rays requires more detailed treatment. Cosmic rays propagate diffusively as they spiral along galactic magnetic field lines. The particles sources are acceleration sites (i.e., supernova remnants) which are distributed inhomogeneously; the sinks are energy losses due to a variety of processes, as well as escape from the galaxy. Cosmic ray propagation is thus properly described by a diffusion equation which accounts for all of these effects as a function of position in the galaxy. However, for our purposes of describing a galactic-averaged cosmic ray flux, the treatment of propagation can be stripped to its essential features. To do this, we make the following simplifying assumptions:

- The shape of the cosmic ray energy spectrum is the same throughout each galaxy and identical to that in the Milky Way (although the normalization may be different).
- The ratios of p to α as well as the ratio of CR electrons to CR protons is constant and same to that in the Milky Way.
- The propagation of cosmic rays in the galaxy can be approximated in terms of the "leaky box" model.

The first two assumptions appeal to a universality in the underlying physics of cosmic ray acceleration by individual supernova remnants. The last assumption treats the galaxy as a single zone to be modeled, as we now see.

[2] The situation above 500 MeV is perhaps less clear. Strong, Moskalenko, & Reimer (2000) have recently suggested that the dominant source in this regime may be inverse Compton scattering of interstellar radiation off a hard electron component.

According to the "leaky box" model, the galaxy is treated as a homogeneous containment environment where CRs propagate freely with a certain probability per unit time to escape. Within the frame of this model the propagation equation becomes

$$\frac{\partial N_i(T,t)}{\partial t} = Q_i(T,t) + \frac{\partial}{\partial T}[b_i(T)N_i(T,t)] - \frac{1}{\tau_{\rm esc}} N_i(T,t). \tag{5}$$

Here $N_i(T,t)$ is the density of particles of species i with kinetic energy between T and $T+dT$. $Q_i(T,t)$ is the source term (particles per volume per time per energy interval dT) including all sources of species i. As we are concerned with p and α particles, the source term Q_i simply represents the supernova acceleration as a source these "primary" species (as opposed to "secondary" particles created in flight, such as Li, Be, and B). Additional spallation contribution and losses are negligible at our level of accuracy. The second term in the right hand side of eq. (5) represents energy losses due to ionization of the ISM, with a rate $b_i(T) = -\left(\partial T/\partial t\right)_i$; in the energy range of interest for π^0 production (> 279 MeV), this can be considered unimportant to a good approximation. The loss of CRs that escape from the "leaky box" is included in the last term, with $\tau_{\rm esc}$ being the mean time spent by the CRs in the containment volume. Although strictly speaking inelastic collisional losses should have also been included in the propagation equation, we have omitted them since the mean free path against collisions is much larger than the one against escape.

If in addition we assume a steady state, the left hand side of eq. (5) vanishes and the propagation equation for protons assumes the simple form

$$0 = Q_p(T) - \frac{1}{\tau_{esc}} N_p(T)\,. \tag{6}$$

Physically, this corresponds to an equilibrium between sources (SN acceleration) and sinks (escape). Since the CR proton flux and the corresponding number density are related via $\phi_p(T) = v_p N_p(T)$, we find that the (propagated) flux is given by

$$\phi_p(T) = \ell_{\rm esc} Q_p(T), \tag{7}$$

where $\ell_{\rm esc} = \tau_{\rm esc} v$ is the mean free path against escape.[3]

Thus, to make further progress in estimating the CR flux $\phi_p(T)$ in the galaxy G, we need to have some understanding of the CR confinement in that galaxy, which enters in eq. (7) through $\ell_{\rm esc}$. This depends on the details of the magnetic field strength and configuration in these galaxies. The detailed physical origin of the confinement scale $\ell_{\rm esc}$ (or equivalently, the diffusion tensor) is as yet uncertain, but is almost certainly related to the structure of and fluctuations in the galaxy's magnetic field (e.g., Berezinskiĭ et al. citebbdgp). Lacking any better knowledge, we will assume confinement conditions similar to those in the Milky Way. Specifically, we will assume $\ell_{\rm esc}$ is the

[3] It is often conventional to define $q_p = Q_p/\rho_{\rm ISM}$ and thus equation (7) implies $\phi_p(T) = \Lambda q_p(T)$ $\Lambda = v_p \tau_{\rm esc}\, \rho_{\rm ISM}$ is the escape pathlength in g cm^{-2}, the "grammage."

same as in the Milky Way. This amounts to an *Ansatz* that the physical properties that determine $\ell_{\rm esc}$ are dominated by local rather than global properties of the host galaxy. This assumption becomes more plausible the more similar G is to the MW, so we expect our approach to yield better results in the cases of M31 and M33 rather than in the cases of the Magellanic Clouds and other irregular galaxies. (Alternatively, one could turn the problem around, and with γ-ray observations of these objects, one can measure or limit the cosmic ray confinement in these objects.)

Under this assumption, the CR flux is proportional to the SN rate in G:

$$\frac{\phi_p^G}{\phi_p^{MW}} = \frac{\mathcal{R}_{\rm G}}{\mathcal{R}_{\rm MW}} = f_{\rm G} \tag{8}$$

So from equations (1) and (8) we get

$$\Gamma_{\pi^0}^G = f_{\rm G}\Gamma_{\pi^0}^{MW} \tag{9}$$

which, following the same procedure that has lead to eq. (4), finally gives

$$q_\gamma^G(> 100{\rm MeV}) = 2.36 \times 10^{-25} f_G \ \text{ photons (s - H atom)}^{-1}\,. \tag{10}$$

Assuming that the CR flux level and spectrum remains the same over the whole galaxy, this emissivity is space-independent. Thus, the $\gamma-$ray flux from galaxy G which lies at a distance d and has a gas content of $M_{\rm gas}$ will simply be

$$F_\gamma^G = \frac{1}{4\pi d^2}\frac{M_{\rm gas}}{m_p}\, q_\gamma^G\,,$$

or, using eq. (10) for q_γ^G,

$$F_\gamma^G(> 100{\rm MeV}) = 2.34 \times 10^{-8} f_{\rm G}\left(\frac{M_{\rm gas}}{10^8 M_\odot}\right)\left(\frac{d}{100\ {\rm kpc}}\right)^{-2} \text{ photons cm}^{-2}\text{ s }^{-1}\,. \tag{11}$$

The largest fraction of the gas present in galaxies is in the form of neutral hydrogen which is detected via 21cm H I observations. The integrated H I mass in a galaxy is related to the integrated H I flux $\int S_v dv$ by the scaling $M_{\rm H\,I} \propto d^2$. This leads to the fortunate circumstance that, although the calculated gas mass for a given galaxy depends on the assumed distance to that galaxy, the ratio

$$\Sigma = \frac{M_{\rm gas}}{d^2}$$

is associated only with quantities which are directly observable and is independent of any assumption on the distance. Thus, eq. (11) can finally be re-written to express the γ-ray flux of photons > 100 MeV from galaxy G

$$F_\gamma^G = 2.34 \times 10^{-8} f_{\rm G}\left(\frac{\Sigma}{10^4 M_\odot {\rm kpc}^{-2}}\right) \text{ photons cm}^{-2}\text{ s }^{-1}\,. \tag{12}$$

in terms of the ratio $f_{\rm G}$ of the supernova rate in G to that of the Milky Way, and the gas mass-to-distance squared ratio Σ.

Table 1: Observed Properties of Selected Local Group Galaxies

Galaxy	SN rate (century^{-1})	Adopted f	Σ $(10^4\ M_\odot$ kpc $^{-2})$ H I	H$_2$	Total
LMC	$0.1^{(2)}$, $0.23\ ^{(3)}$,$0.49^{(4)}$	0.14	$22 \pm 6^{(1),(11),(12),(13)}$	$4.63^{(13)}$	26.6
SMC	$0.065^{(3)}$, $0.12^{(4)}$	0.04	$17 \pm 4^{(1),(5)}$	$0.76^{(13)}$	17.8
M31	$0.9\ ^{(9)}$, $1.21^{(4)}$, $1.25\ ^{(7)}$	0.45	$0.9 \pm 0.2^{(1),(6)}$	$0.06^{(16)}$	0.92
M33	$0.28^{(8)}$, $0.35^{(9)}$, $0.68^{(4)}$	0.17	$0.26 \pm 0.05^{(1)}$	$0.004^{(17)}$	0.264
NGC6822	$0.04^{(10)}$	0.02	$0.05 \pm 0.02^{(1)}$	$0.006^{(18)}$	0.056
IC10	$0.082\text{-}0.11^{(14)}$	0.04	$0.016 \pm 0.003^{(15)}$	$\gtrsim 10^{-5\ (19)}$	0.016

References: (1) Huchtmeier & Richter (1989), references therein; (2) Chu & Kennicutt (1988); (3) Kennicutt & Hodge(1986); (4) Tammann *et al.* (1994); (5) Stanimirović *et al.* (1999); (6) Braun & Walterbos (1992); (7) Braun & Walterbos (1993); (8) Gordon *et al.* (1998); (9) Berkhuijsen (1984); (10) Timmes & Woosley (1997); (11) Luks & Rohlfs (1992); (12) Kim *et al.* (1998); (13) Westerlund (1997); (14) Thronson *et al.* (1990); (15) Shostak & Skillman (1989), also references therein (16) Dame *et al.* (1993); (17) Wilson & Scoville (1989); (18) Israel (1997); (19) Wilson & Reid (1991)

3. Data

Equation (12) shows that the information we need to calculate the expected γ-ray flux from each galaxy is the SN rate of the galaxy, and the ratio Σ. A summary of these data and the relevant references are presented in Table 1. The indicated ranges are the span in the published observational data and are not representative of the error of each measurement as estimated by the corresponding authors. This should give a sense of the systematic uncertainties, but one should bear in mind that the overall error could be larger, particularly for the supernova rates. The value quoted in the Σ column is the mean value of all the measurements found in the indicated references while the error is just the square root of the sample variance.

In order to calculate f_G we also need the SN rate of the MW. Different authors have produced results which cover a range of roughly an order of magnitude, depending on the method of calculation. The three main methods used are extragalactic SN discoveries, SN-related Galactic data relating to massive star formation, chemical evolution, and nuclear γ-ray lines, and analysis of the historical record of Galactic SN explosions. Dragicevich *et al.* (1999) critically surveyed $\mathcal{R}_{\rm MW}$ determinations by different methods. The different results quoted in that work are given in Figure 1.

As noted by Dragicevich *et al.* , the Galactic supernova rates estimated using data from historical supernovae tend to be higher than those based on extragalactic or nuclear/γ-ray line constraints. This discrepancy might arise if our location in the Galaxy is "special"–e.g., near a spiral arm where star formation is enhanced. In addition, Hatano, Fisher, & Branch (1997) suggest that a large fraction ($\sim$ 50%) supernovae are "ultradim" ($M_V \sim -13$), possibly due to localized

shrouding effects. Such a population would be missed in extragalactic surveys, but would appear in the historical record, and would still contribute to nucleosynthesis and accelerate cosmic rays. In our study, we will use extragalactic supernova data for Local Group objects, and thus the lower estimates of the Galactic supernova rate are the appropriate ones to use. As a "best bet" we will adopt Dragicevich *et al.* 's (1999) recommended value of 2.5 SN per century.

4. Results

We now combine eq. (12) with the data presented in Table 1 to predict $\gamma-$ray flux levels for photons with energies above 100 MeV originating in the interaction between cosmic rays and interstellar medium in galaxies of the Local Group. We will use the Magellanic Clouds to verify the applicability of our method, since for these systems we can compare our predictions with both EGRET observational results (detection for the LMC, upper limit for the SMC) and other predictions using models based on entirely different assumptions: dynamic equilibrium for the LMC (Fichtel *et al.* 1991), constant cosmic ray proton-to-electron ratio for the SMC (Sreekumar & Fichtel 1991).

We will then use our model to proceed to predictions of $\gamma-$ray fluxes in galaxies of the Local Group for which there have been either no previous studies or, in the case of M31, only partial treatments. For the latter, Özel & Berkhuijsen (1987) based on the gas content alone arrived at a result in which the cosmic ray flux scaling between the Milky Way and M31 was treated as a free multiplicative parameter, left to be decided observationally.

Our predictions, and their implications for GLAST, are summarized in Table 2, with detailed discussion of each galaxy appearing below. In Table 2, all values refer to γ-rays > 100 MeV. The "GLAST Significance" column refers to the formal significance expected to be achieved after a 2-year (nominal GLAST duty cycle) and 10-year (GLAST lifetime goal) all-sky survey. The "On-Target 5 σ Exposure Time" column refers to the total exposure *of the object* needed to achieve a 5 σ detection. When GLAST is operating in the normal sky-scanning mode, each individual source is in the field of view for only $\sim 20\%$ of the time for each duty cycle, so the GLAST operation time required to achieve a detection of the same significance is typically 5-6 times the on-target exposure time quoted (assuming a field of view for GLAST between 2 and 2.4 sr). All significances and exposure times were calculated according to the GLAST specifications as described in De Angelis (2000) and in the GLAST Science Requirements Document (`http://glast.gsfc.nasa.gov/science/aosrd`). We have used an effective collector area of 8000 cm^2 (GLAST requirement, 0.8$\times$ GLAST goal), and taken into account the (Galactic and extragalactic) $\gamma-$ray background noise levels as measured by EGRET for the Galactic coordinates of each object. Whenever the angular extent of an object in the sky (as derived from 21 cm maps) exceeded the 1-photon angular resolution of GLAST, the actual size of the object was used as the relevant solid angle for the collection of background noise. The same calculation, when applied to a point source of flux 2×10^{-9}photons cm^{-2} s^{-1} located at high Galactic latitude, predicted a 5-σ detection after a 2-year all-sky survey, in accordance to the

Table 2: Predicted Gamma-Ray Flux and GLAST Requirements for Selected Local Group Galaxies

	Flux > 100 MeV (photons $\mathrm{cm^{-2}\,s^{-1}}$)		GLAST Significance		GLAST On-Target
Galaxy	Prediction	EGRET Value/Limit	2 years	10 years	5σ Exposure Time
LMC	11×10^{-8}	$(14.4 \pm 4.7) \times 10^{-8}$	$42\ \sigma$	$93\ \sigma$	4.6×10^{-3} yr
SMC	1.7×10^{-8}	$< 4 \times 10^{-8}$	$19\ \sigma$	$43\ \sigma$	2.1×10^{-2} yr
M31	1.0×10^{-8}	$< 1.6 \times 10^{-8}$	$13\ \sigma$	$31\ \sigma$	4.1×10^{-2} yr
M33	0.11×10^{-8}	N/A	$1.9\ \sigma$	$4.1\ \sigma$	2.31 yr
NGC6822	2.6×10^{-11}	N/A	$0.04\ \sigma$	$0.09\ \sigma$	$\gg 10$ yr
IC10	2.1×10^{-11}	N/A	$0.02\ \sigma$	$0.05\ \sigma$	$\gg 10$ yr

sensitivity derived in the GLAST Science Requirements Document.

4.1. Magellanic Clouds

4.1.1. Large Magellanic Cloud

The LMC is the only galaxy other than the Milky Way for which there has been a positive detection of its diffuse $\gamma-$ray emission, and is therefore the only one of the systems of interest for which any prediction can be directly tested against observations.

For the LMC, Table 1 suggests a mean Σ equal to $26.6 \times 10^4 M_\odot\,\mathrm{kpc}^{-2}$ and a mean SN rate of 0.27 century^{-1} which, combined with a Galactic SN rate of 2.5 century^{-1}, gives $f_{\rm LMC} = 0.11$. Inserting these data in eq. (12) we derive a γ-ray flux for photons with energies > 100 MeV of 6.8×10^{-8} photons $\mathrm{cm^{-2}\,s^{-1}}$.

However, of the 3 references quoted in Table 1 for the SN rate of the LMC, the lowest one (ref. (2) in the table, equal to 0.1 SN century^{-1}), which is based on a count of observed SN remnants, is derived only as a lower limit to the LMC SN rate. The other two estimates are based on extragalactic SN discoveries in morphologically similar galaxies (ref. 4 in Table 1) and on the massive star formation rate (ref. 3 in Table 1). If we use the mean value of the latter two as our best estimate for $\mathcal{R}_{\rm LMC}$ we get $f_{\rm LMC} = 0.14$.

As far as the gas mass is concerned, although the more recent 21cm surveys tend to give rather low values for Σ (Luks & Rohlfs 1992, Kim *et al.* 1998), the gas mass estimates in those cases are assuming an optically thin medium. However, recent studies of the cool gas in the LMC by Marx-Zimmer *et al.* (2000) are not in favor of this assumption, which indicates that the gas masses might in fact be significantly underestimated. On this basis, we will adopt for our calculation the higher estimate from Westerlund (1997) which predicts a $\Sigma_{\rm H\,I} = 28 \times 10^4 M_\odot\,\mathrm{kpc}^{-2}$, and thus $\Sigma_{\rm tot} = 32.6 \times 10^4 M_\odot\,\mathrm{kpc}^{-2}$.

These values of f and Σ, if used in eq. (12), yield a total γ-ray flux of

$$F_{\gamma}^{\rm LMC} = 11 \times 10^{-8}\,\text{photons cm}^{-2}\text{ s}^{-1}\,. \tag{13}$$

This value is in excellent agreement with the observed value of $(14.4\pm4.7)\times10^{-8}$ photons cm^{-2} s $^{-1}$ (Hartman *et al.* 1999). This consistency gives us confidence in our method of computing galactic cosmic ray fluxes.

Indeed, one could even turn the argument around, and tentatively interpret this agreement as an indication that the cosmic ray confinement in the LMC is comparable to that of the Milky Way, $\Lambda_{\rm esc} \sim 10$ g cm^{-2}. Given the large differences in the size and structure of these two galaxies, this result would suggest that cosmic ray confinement is not strongly dependent on a galaxy's global properties, but more closely connected to local physics, such as the magnetic field strength configuration and fluctuations. If confirmed, therefore, this result would give new and unique information about the nature of cosmic ray confinement and propagation. As noted below (§4.2), this result can be tested by combining the flux measurements for multiple Local Group sources, particularly by comparing the LMC to the Small Magellanic Cloud.

Of course, the uncertainties in the observational data, especially the Galactic SN rate, can have an important impact on our calculation. For example, if we adopt a Galactic SN rate of 1 century^{-1} and keeping the same values for all other data, the LMC flux could be as large as 27 $\times10^{-8}$photons cm^{-2} s^{-1} On the other hand, if the Galactic SN rate is as high as 5 century^{-1}, this estimate would drop to 5.3 $\times10^{-8}$ photons cm^{-2} s^{-2}.

With these caveats in mind, our best estimate for the flux gives a very strong detection (formally, at the 42σ level) in the first 2 years of sky-scanning GLAST operation, with the 5-σ detection feasible after an on-target observation time of less than 2 days.

4.1.2. Small Magellanic Cloud

The $\gamma-$ray flux level of the Small Magellanic Cloud has been the object of both theoretical and observational studies in the past, which have been used to resolve the debate of the origin of the cosmic rays: if the origin of the cosmic rays were cosmological and the level of the CR flux were universal the $\gamma-$ray flux should have been easily detectable by EGRET (Sreekumar & Fichtel, 1991). However, the SMC was not detected by EGRET, and an observational upper limit was placed instead on its $\gamma-$ray flux. (Sreekumar *et al.* 1993, Lin *et al.* 1996).

This observational upper limit was also lower than the value Sreekumar & Fichtel (1991) predicted if the cosmic rays, gas and magnetic fields in the SMC were in a state of dynamic equilibrium. Thus, Sreekumar *et al.* (1993) attributed the non-detection of the SMC by EGRET to poor confinement of cosmic rays in the SMC.

In the framework of our model, we will investigate whether CR flux levels of the SMC low

enough so as to prohibit its detection by EGRET can also be explained in terms of a low supernova rate and consequently a low cosmic ray acceleration rate, even if we assume similar confinement conditions with those of the Milky Way. Although the differences between the morphologies of the MW and the Magellanic Clouds might raise questions concerning the validity of the latter assumption, the good agreement of our results with observations in the case of the LMC encourage the application of our method in the case of the SMC as well.

For the SMC, the mean value of Σ is equal to $17.8 \times 10^4 M_\odot$ kpc^{-2} and the average of the quoted SN rates is 0.09 SN per century (Table 1). Thus, eq. 12 (using again a $\mathcal{R}_{\rm MW}$ equal to 2.5 century^{-1}) predicts a γ-ray flux of

$$F_\gamma^{\rm SMC} = 1.7 \times 10^{-8} \text{ photons cm}^{-2}\,\text{s}^{-1}\,. \tag{14}$$

This value is consistent with the current observational upper limit of 4×10^{-8} photons cm^{-2} s^{-1} of Lin *et al.* (1996). Using this "best bet" value for the SMC $\gamma-$ray flux, we find that GLAST will detect the SMC with a 19 σ significance after a 2-year all-sky survey. The total exposure time needed to achieve a 5 σ detection is only 8 days.

We thus see that the observed SN rate for the SMC is, by itself, sufficient to explain the observational upper limit placed by EGRET, even under the assumption of confinement conditions that do not differ from those in the Milky Way. Whether confinement in the SMC plays an additional role in lowering the global cosmic ray and subsequently $\gamma-$ray flux is a very interesting question, left to be answered observationally by GLAST.

If now we use the upper limit values for the $\Sigma_{\rm SMC}$ and $f_{\rm SMC}$ of $21.8 \times 10^4 M_\odot$ kpc^{-2} and 0.05 correspondingly, the resulting $\gamma-$ray flux reaches 2.6×10^{-8} photons cm^{-2} s^{-1}, still below the current observational upper limit. In the other end of the range, using the lowest estimates for the Σ and $\mathcal{R}$ of the SMC, the result we get is equal to 0.85×10^{-8} photons cm^{-2} s^{-1}, well above the anticipated sensitivity of GLAST. In fact, the SMC $\gamma-$ray flux would be still detectable by GLAST even if, in addition to using the lowest available values for Σ and $\mathcal{R}_{\rm SMC}$, we adopted a Galactic SN rate higher than our "best bet" by a factor of 3.

Although our assumption for a "leaky box" CR confinement is more questionable in the case of the Magellanic Clouds, our prediction is consistent the upper limit set by EGRET. Furthermore, it coincides with the detailed calculations of Sreekumar & Fichtel (1991). These authors used synchrotron radiation measurements to deduce the cosmic ray intensity and distribution in the SMC (assuming a CR proton-to-electron ratio same as that of the MW) and predicted a total flux of γ-rays above 100 MeV equal to 1.7×10^{-8} photons cm^{-2} s^{-1}. The perfect agreement between this prediction and ours is fortuitous, but nevertheless increases our confidence in our basic model. In the cases of galaxies such as M31 and M33, we expect the CR confinement conditions to be much more similar to those in the MW (observations indicating the opposite would not only be a surprising but a very interesting result in itself). Thus, we expect our predictions for these galaxies to be, within our uncertainty limitations, even more reliable.

4.2. M31

The mean observed value of Σ for M31 is $0.92 \times 10^4 M_\odot$ kpc^{-2} while the average of $\mathcal{R}_{\rm M31}$ as measured with all 3 different methods (observations of SN remnants, star formation rates and morphology arguments) is 1.12 per century (Table 1). The average $\mathcal{R}_{\rm M31}$ corresponds to an M31/MW supernova rate ratio $f_{\rm M31} = 0.45$. It is worth pointing out that M31 has an unusually low Hα and far infrared emission (e.g., Pagini et al. citepagnini), which imply a low star formation rate, and hence a low Type II supernova rate for such a large galaxy. As we will see, GLAST should detect M31, an thus provide an important new measure of the M31 supernova rate.

Using our adopted gas content and supernova rate for M31, eq. (12) then predicts a total γ-ray flux for energies above 100 MeV

$$F_\gamma^{\rm M31} = 1.0 \times 10^{-8} \, \text{photons cm}^{-2} \text{ s}^{-1} \, . \tag{15}$$

This value is consistent with the observational upper limit of 1.6×10^{-8} photons cm^{-2} s^{-1} set by Blom *et al.* (1999), but only slightly lower than the EGRET sensitivity. As we see in Table 2, our predicted $\gamma-$ray flux for M31 would be detected by GLAST in its first 2-year all-sky survey with a 14 σ significance. After a projected lifetime of 10 years, and assuming continuous sky-scanning operation, this significance would rise to 31 σ.

Our calculation gives theoretical support to the case made by Digel et al. (2000), who noted that if the flux from Andromeda lies just below the Blom et al. limit, then GLAST will readily be able to detect it. Here we find that indeed, the flux should be just at the level of 1×10^{-8} photons cm^{-2} s $^{-1}$ suggested by Digel et al., though the uncertainty range is considerable, as we now see.

To estimate the effect of the various uncertainties in our calculation, we observe that if we had used the highest available observed values for Σ and $\mathcal{R}_{\rm M31}$ as given in Table 1 but kept the Galactic SN rate fixed at 2.5 per century, the resulting flux of 1.3×10^{-8} photons cm^{-2} s^{-1} would still be lower than the observational upper limit. With Σ and $\mathcal{R}_{\rm M31}$ values both at the upper end of their respective ranges, $F_\gamma^{\rm M31}$ would remain below the EGRET limit for $\mathcal{R}_{\rm MW}$ as low as 2 per century.

At the other end of the range of the available M31 data, using a Σ as low as $0.7 \times 10^4 M_\odot$ kpc^{-2} and $\mathcal{R}_{\rm M31}$ of 0.9 per century, we derive a predicted flux of 0.6×10^{-8} photons cm^{-2} s^{-1}, still easily above the expected GLAST sensitivity. If in addition we take into account the uncertainty in the $\mathcal{R}_{\rm MW}$, we can see that even with the most pessimistic estimates for the M31 gas content and SN rate, the γ-ray flux remains above the GLAST detectability limit for a Galactic SN rate up to 7 per century.

In sum, our analysis leads to the robust prediction that a γ-ray observatory with sensitivity similar to that expected for GLAST will detect the diffuse $\gamma-$ray signature of M31.

Once there is a positive detection, depending on the strength of the signal and the available spatial resolution, this opens several avenues of further analysis:

- The spatial distribution of neutral hydrogen in M31 has been observed to exhibit an asymmetry, with the west part of the galaxy having a significantly lower column density than the northeast part. For the relevant γ-ray fluxes of the two areas (a few times 10^{-9} up to 10^{-8} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$), the angular resolution of GLAST will be $10' - 20'$ (Digel *et al.* 2000). Given the $\sim 2^\circ$ size of M31 in 21 cm (which is the relevant angular size for $\gamma-$ray emission), this asymmetry is easily within the angular resolution capabilities of GLAST and is thus expected to be observed in the $\gamma-$ray signal as well. If the M31 flux is high enough, one might even hope to observe effects of the magnetic torus (e.g., Beck, Brandenburg, Moss, Shukurov, & Sokoloff (1996)) and star forming ring (e.g., Pagani et al. (1999)) at radius 10 kpc. A similar morphological feature in the Milky Way, the H_2 ring extending in radius from 4 to 8 kpc (e.g., Bronfman *et al.* 1988) was first detected in early $\gamma-$ray surveys and then shown to be consistent with subsequent CO molecular surveys (Stecker, Solomon, Scoville, & Ryter 1975).

- An observational measurement of the diffuse $\gamma-$ray flux from M31 could be used to reverse the arguments presented in section 2 and make inferences regarding the cosmic ray flux in M31: From the $\gamma-$ray flux as measured from Earth, F_γ^{M31}, and using the distance and gas content of M31, we can calculate the γ-ray production rate per target H-atom. This result, combined with an assumption for the cosmic ray energy spectrum, would provide information on the cosmic ray flux level in M31 which could then be compared with the MW cosmic ray flux to determine whether they are comparable and whether the MW has a typical cosmic ray activity for galaxies with similar morphology. (Note here that we assume that the contribution from point sources in M31 would be negligible.)

- A measured value of the $\gamma-$ray flux from M31 could also be used to determine the ratio of the supernova rates between M31 and the Milky Way, assuming that the gas content of M31 is known to a good accuracy:

$$f_{\mathrm{M31}} = \frac{\mathcal{R}_{\mathrm{M31}}}{\mathcal{R}_{\mathrm{MW}}} = 0.45 \left(\frac{F_\gamma^{\mathrm{M31}}}{10^{-8}\,\mathrm{photons\,cm^{-2}\,s^{-1}}} \right) \tag{16}$$

  using eq. 12. This ratio could then be used e.g. to determine the MW supernova rate or to to infer the ratio of formation rates for high-mass stars, and, assuming a constant initial mass function, the ratio of total star formation rates between the two galaxies. (Here we rely on our assumption that all cosmic rays are produced by supernovae.)

These last two points can be self-consistently checked once GLAST has information on more than one extragalactic source. For example, the ratios of the flux measurements *among* the extragalactic sources is a direct measure of the ratios of the cosmic ray densities. In our model, these ratios gives the ratio of the product of $\mathcal{R}\ell_{\mathrm{esc}}$. Thus, with information about the supernova rates, one can directly measure the ratios of cosmic ray confinements; this allows one to compare these values between the LMC and SMC, and to contrast the clouds with M31 (and M33). One

might then assume, in the case of the clouds, that their confinements are equal, and compare the inferred supernova rates with values estimated by other means. Alternatively, one could assume (as we have) that the confinements are these same as in the MW, and then use the ensemble of measurements of Local Group sources to reduce the uncertainty in the inferred Milky Way SN rate.

Another potential cross-check would come from the comparison of Local Group > 100 MeV emission and γ-ray line emission from radioactive decays (Timmes & Woosley (1997)). The line flux is sensitive to the supernova rate only, so that the ratio of the > 100 MeV continuum to the lines gives direct information about the cosmic ray confinement. Unfortunately, such a comparison may have to wait, as the Timmes & Woosley calculations predict that the line fluxes lie below the expected sensitivity of the forthcoming *International Gamma-Ray Astrophysics Laboratory* (INTEGRAL) mission.

Even a non-detection of M31 in high energy γ-rays would be, apart from very surprising, a result of high theoretical interest, since the only parameter entering our calculations other that f and Σ is $\ell_{\rm esc}$ (the escape mean free path)–which in turn depends on the confinement conditions of the cosmic ray nuclei in M31. A non-detection would thus lead us to reconsider our assumption of similar confinement conditions with M31. Such a result would provide observational clues for the confinement in an extragalactic environment (morphologically similar to the Milky Way) and for the nucleonic component of cosmic rays.

4.3. Other Local Group Galaxies

Using the mean values for the gas content-related Σ and the supernova rate shown in Table 1 for the case of M33, eq. (12) gives a $\gamma-$ray flux of

$$F_\gamma^{\rm M33} = 0.11 \times 10^{-8} \text{ photons cm}^{-2}\text{ s}^{-1}\,, \tag{17}$$

which is slightly below the sensitivity limit of GLAST. As seen in Table 2, after a 10 year sky survey, the detection is at the 4.2σ level (comparable to the current LMC significance). If we use the highest available estimates for the M33 gas content and supernova rate, the flux would rise to 0.2×10^{-8} photons cm^{-2} s^{-1}, which would allow for a 5σ detection after a sky survey of 4.39 years. Alternatively, even if eq. (17) is accurate, M33 will be detectable at the 5σ level within 10 years if the GLAST effective area and field of view achieve their “goal” levels (as opposed to the “required” levels we have used).

Thus, there is grounds for optimism that a detection might be possible, if either the gas content and supernova rate have been slightly underestimated, or the actual sensitivity of the GLAST observatory is slightly improved as compared to the current prediction. We therefore urge observers to be aware of the possibility of detecting (or placing a limit on) flux from M33.

The next best candidates for detection (highest combination of Σ and f) in the local group are NGC6822 and IC10. However, using the data shown in Table 1 for these galaxies, eq. (12)

predicts fluxes which are comparable within our uncertainty limits and equal to about 0.002×10^{-8} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Such tiny fluxes would require exposure GLAST times of decades, and thus appear to lie beyond reach for the foreseeable future.

Thus, apart from the Magellanic Clouds, M31 and M33, no other Local Group galaxy seems to be a good candidate for the detection of its diffuse γ-ray flux by γ-ray observatories in the near future. There might, however, be other promising candidates, which lie outside the Local Group. Starburst galaxies, despite the fact that they lie at a greater distance that Local Group galaxies, have a significantly higher supernova rate, as well as high gas contents, which should result to high γ-ray production rate and a flux that might be detectable by highly sensitive observatories (Paglione *et al.* 1996).

5. Discussion

Diffuse, high-energy ($\gtrsim$ 100 MeV) γ-rays provide the most direct evidence for the extension of the cosmic ray ion component throughout our Galaxy. The observation of such radiation from extragalactic systems would provide unique information, as the mere detection of high-energy γ-rays confirms the presence of cosmic ray ions, and the photon flux can be used to infer the cosmic ray flux, and thus can constrain extragalactic cosmic ray properties. Unfortunately, the only extragalactic object detected thus far is the LMC (Sreekumar *et al* (1992)).

In anticipation of future high-energy γ-ray observatories such as GLAST, we have estimated the γ-ray flux due to diffuse emission for Local Group galaxies. To do this, we have used a simple "leaky box" model of cosmic ray propagation, and taken supernova blasts to be the engines of cosmic ray acceleration. Our model makes different assumptions than Fichtel *et al.* 's (1991) more detailed treatment of the LMC, but both give similar results, and are in reasonable agreement with LMC γ-ray observations.

Applying our model to other Local Group galaxies, we predict that M31 has a γ-ray flux above 100 MeV of about 1.0×10^{-8} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, with an uncertainty of about a factor of 3. Fortunately, despite this large error budget, we can conclude that M31 should be observable by GLAST, and we therefore strongly urge that M31 be looked for in GLAST maps. A detection will provide important and unique information about cosmic rays in a galaxy similar to our own. In addition, we find that the SMC should have a flux of about 1.4×10^{-8} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, readily detectable by GLAST. The comparison among the LMC, SMC, and M31 γ-ray luminosities will provide new information about cosmic ray densities and confinement, and supernova rates, in these systems and in the Milky Way.

The high-energy γ-ray flux from other Local Group galaxies is much smaller. Other than M31 and the Magellanic clouds, the only system that is potentially observable is M33, with a flux of about 0.1×10^{-8} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. If GLAST can stretch to reach its sensitivity goals, this too will be observable. All other Local Group galaxies have emission that is at least 2 orders of magnitude

smaller.

We thank David Branch, Jim Buckley, You-Hua Chu, Robert Gruendl and Kostas Tassis for enlightening discussions. We thank the referee for constructive comments which have improved this paper. The work of V.P. was partially supported by a scholarship from the Greek State Scholarship Foundation.

REFERENCES

Akyüz, A., Brouillet, N. & Özel, M.E. 1991, A&A, 248, 419

Beck, R., Brandenburg, A., Moss, D. Sukurov, A., & Sokoloff, D. 1996, ARAA, 34, 155

Berezinskiĭ, V.S., Bulanov, S.V., Dogiel, V.A., Ginzburg, V.L., & Ptuskin, V.S. 1990, Astrophysics of Cosmic Rays, Amsterdam: North-Holland

Berkhuijsen, E.M. 1984, A &A, 140, 431

Blom, J. J., Paglione, T. A. D. and Carramiñana, A. 1999, ApJ, 516, 744

Braun, R. & Walterbos, R.A.M. 1992, ApJ, 386, 120

Braun, R. & Walterbos, R.A.M. 1993, A&A, 98, 327

Bronfman, L., Cohen, R. S., Alvarez, H., May, J., & Thaddeus, P. 1988, ApJ, 324, 248

Cavallo, G. & Gould, R.J. 1971, Nuovo Cimento, 2B, 77

Chu, Y.-H. & Kennicutt, R.C. Jr. 1988, ApJ, 96, 6

Combi, J.A., Romero, G.E. & Benaglia, P. 1998, A&A, 333, L91

Cram, T.R., Roberts, M.S. & Whitehurst, R.N. 1980, A&AS, 40, 215

Dame, T. M., Koper, E., Israel, F. P. & Thaddeus, P. 1993, ApJ 418, 730

Dermer, C. D. 1986, A&A, 157, 223

De Angelis, A. 2000, to be published in the Proceedings of the 3rd International Workshop “New Worlds in Astroparticle Physics,” astro-ph/0009271

Digel, S.W., Hunter, S.D. & Mukherjee, R. 1995, ApJ, 441, 270

Digel., S.W., Moskalenko, I.V., Ormes, J.F., Sreekumar, P., & Williamson, P.R. 2000, AIP Conf.Proc., 528, 449

Dragicevich, P.M., Blair, D.G. & Burman, R.R. 1999, MNRAS, 302, 693

Ellison, D.C., Drury, L.O., & Meyer, J.P. 1997, ApJ, 487, 197

Fichtel, C.E. & Kniffen, D.A., A&A, 134, 13

Fichtel, C.E., Özel, M.E., Stone, R.G. & Sreekumar, P. 1991, ApJ, 374, 134

Gordon, S.M., Kirshner, R.P., Long, K. S., Blair, W. P., Duric, N. & Smith, R.C. 1998, ApJS, 117, 89

Hartman R.C. *et al.* 1999, ApJS, 123, 79

Hatano, K., Fisher, A., & Branch, D. 1997, MNRAS, 290, 360

Huchtmeier, W. K. 1973, A&A, 22, 91

Huchtmeier, W. K., & Richter, O. 1989, A general catalog of H I observations of galaxies: the reference catalog, (Springer-Verlag: New York)

Huchtmeier, W. K, Karachentsev, I.D., Karachentseva, V.E. & Ehle, M. 2000, A&A 141, 469

Hunter, S.D. *et al* 1997, ApJ 481, 205

Israel, F. P., 1997, A&A 317, 65

Kennicutt, R. C., Jr. & Hodge, P. W. 1986, ApJ, 306,130

Kim, S., Staveley-Smith, L., Dopita, M.A., Freeman, K.C., Sault, R.J., Kesteven, M.J. & McConnell, D. 1998, ApJ, 503, 674

Koyama, K. *et al.* 1995, Nature, 378, 255

Lin, Y.C. *et al.* 1996, ApJS, 105, 331

Long, K.S., Blair, W.P., Kirshner, R.P. & Winkler, P.F. 1990, ApJS, 72, 61

Luks, Th. & Rohlfs, K. 1992, A & A, 263, 41

Marx-Zimmer, M, Herbstmeier, U. Dickey, J.M., Zimmer, E., Staveley-Smith, L. & Mebold, U. 2000, A & A, 354, 787

Mori, M. 1997, ApJ, 478, 225

Özel, M.E. & Berkhuijsen, E.M. 1987, A&A, 172, 378

Özel, M.E. & Fichtel, C.E. 1988, ApJ 335, 135

Pagani, L., et al. 1999, A&A, 351, 447

Paglione, T.A.D., Marscher, A.P., Jackson, J.M. & Bertsch, D.L. 1996, ApJ, 460, 295

Shostak, G.S. & Skillman, E.D. 1989, A & A, 214, 33

Sreekumar, P. & Fichtel, C.E. 1991, A&A, 251, 447

Sreekumar, P. *et al* 1992, ApJ, 400, L67

Sreekumar, P. *et al* 1993, Phys.Rev.L., 70, 127

Sreekumar, P. *et al* 1998, ApJ, 494, 523

Stanimirović, S.,Staveley-Smith, L., Dickey, J.M., Sault, R.J. & Snowden, S.L. 1999, MNRAS, 302, 417

Stecker, F.W. 1970, Ap. and Space Sci., 6, 377

Stecker, F.W. 1973, ApJ, 185, 499

Stecker, F.W., Solomon, P.M., Scoville, N.Z. & Ryter, C.E. 1975, ApJ, 201, 90

Stecker, F.W. 1988, in Cosmic Gamma Rays, Neutrinos and Related Astrophysics, ed. M.M. Shapiro & J.P. Wefel (Dordrecht:Reidel), 85

Stephens, S.A. & Badhwar, G.D. 1981, Ap&SS, 76, 213

Strong, A.W. 1996, SSRv, 76, 205

Strong, A.W., Moskalenko, I.V., & Reimer, O. 2000, ApJ, 537, 763

Tammann, G.A., Löffler, W. & Schröder, A. 1994, ApJS, 92, 487

Timmes, F. X. & Woosley, S. 1997, ApJ, 489, 160

Thronson, H. A. Jr., Hunter, D. A., Casey, S. & Harper, D. A. 1990. ApJ, 355, 94

Westerlund, B.E. 1997, The Magellanic Clouds, (Cambridge: Cambridge Univ. Press), 28

Wilson, C.D. & Scoville, N. 1989, ApJ 347, 743

Wilson, C.D. & Wilson, Reid, I. N. 1991, ApJL 366, 11

This preprint was prepared with the AAS LaTeX macros v5.0.

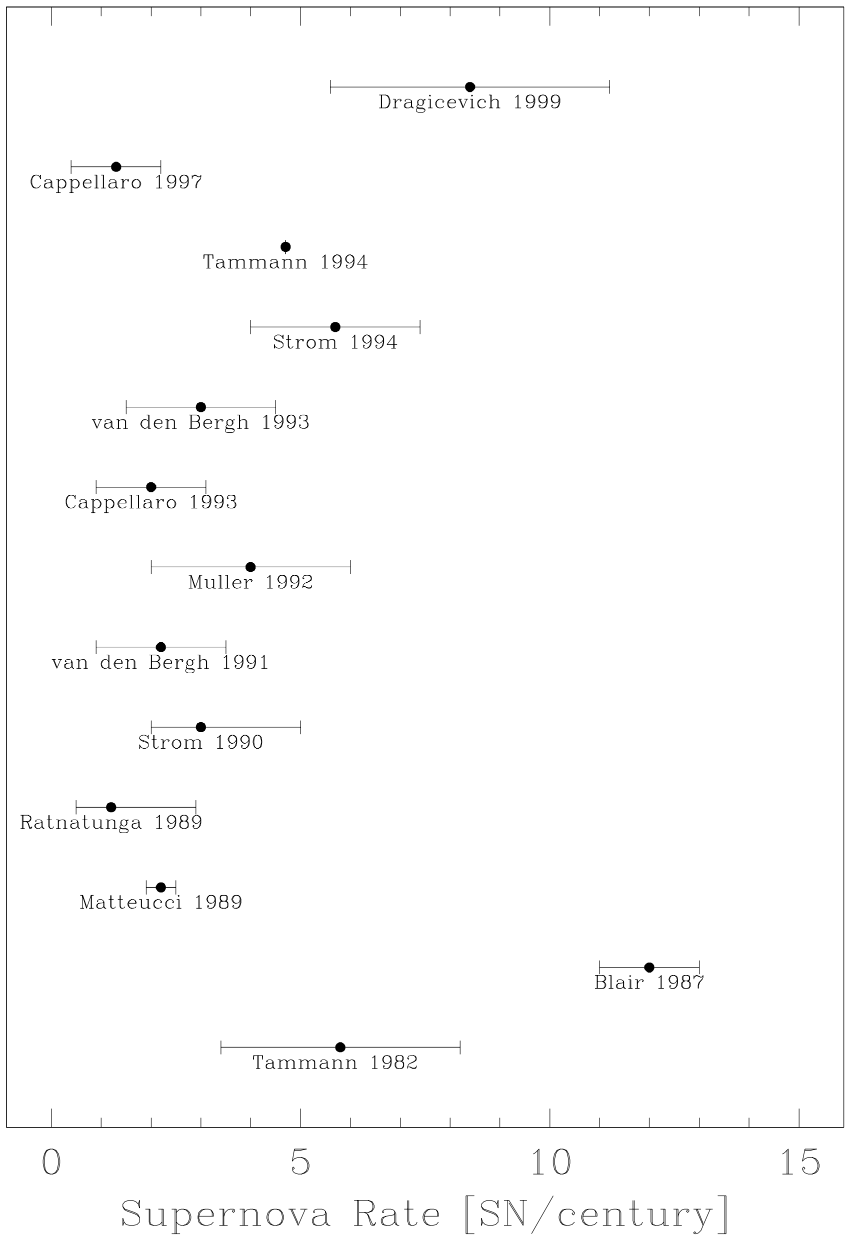

Fig. 1.— Milky Way supernova rates as calculated by different authors, from the tabulation of Dragicevich *et al.* (1999). The estimates from extragalactic SN discoveries have been standardized to $h = 0.75$ and a Milky Way blue luminosity of $(2.3 \pm 0.6) \times 10^{10} L_{\odot,B}$.